NASA Hybrid Gas-Electric Propulsion (HGEP) Subproject

Advanced Air Transport Technologies (AATT)

Progress update for

One Boeing NASA Electric Aircraft Workshop

March 22, 2017

Arlington VA

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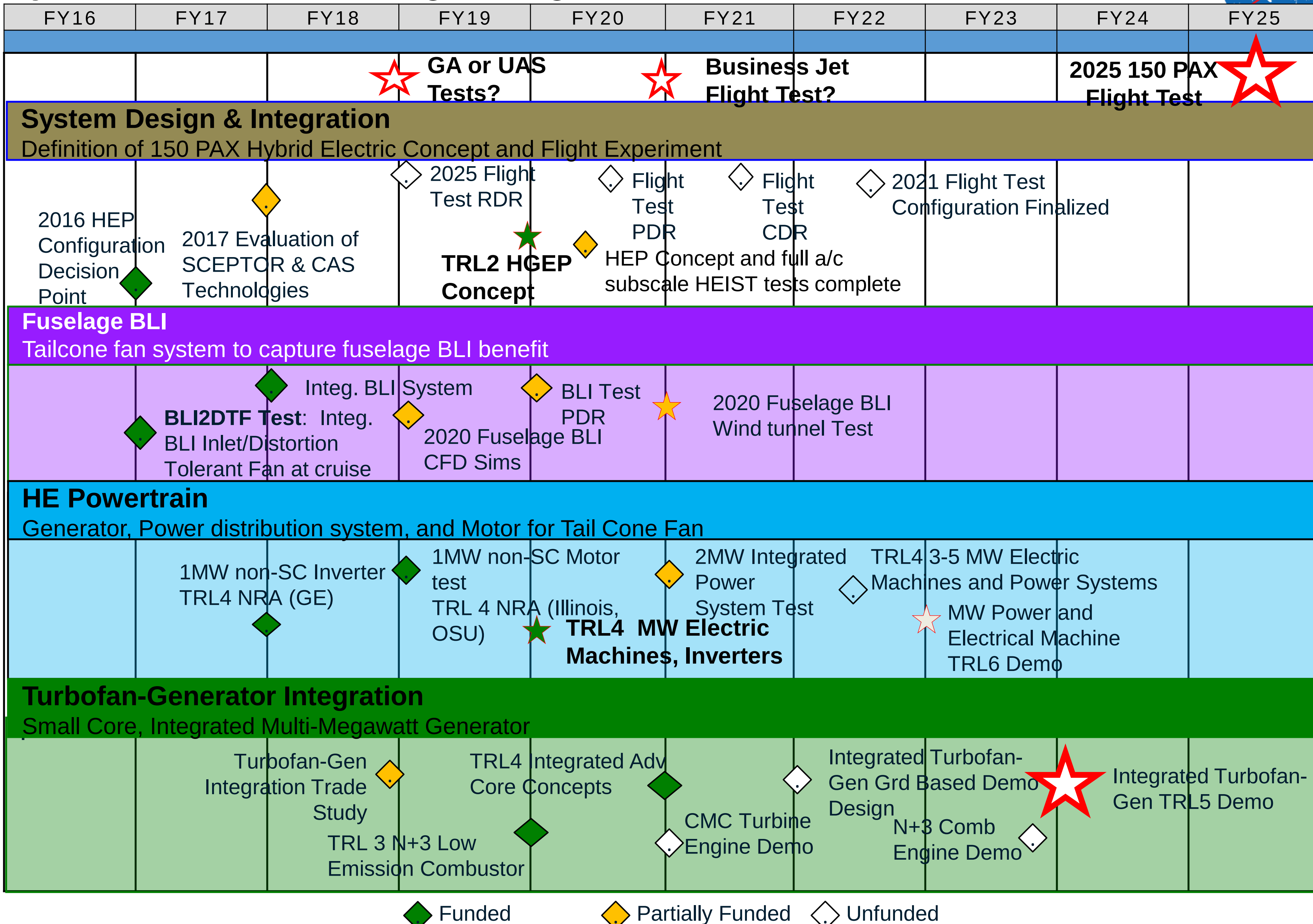
Presentation Outline

– Notional Schedule for HEP Technologies Flight Demonstrators
– Component Technology Investment Method
– Summary of Contracts resulting from HGEP NASA Research Announcements
– Enabling Materials R&D
– Testbed Status
– Project Summary

Notional, For Planning Purposes Only

Hybrid Electric Technologies Flight Demonstrator



Component Technology Investment Method

Baseline Future Vehicle
Predicted Available Technologies → Concept that closes w/ Net Benefit → Derive Key Powertrain Performance Parameters → Dissect Contributors to Weight and Loss in SOA → Derive Key Subcomponents Performance Parameters

Vehicle Systems Studies including missions profile, propulsion system, CFD

Calculated power and efficiency curves, etc.

Materials and electromagnetic properties, EMI, fault tolerance, etc.

Concept A

Concept B

…

Build, test, fly, learn at successively higher power and voltage levels

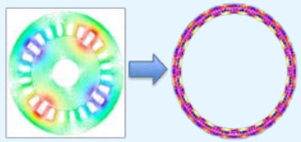
- Validate the vehicle architecture as well as component performance

Investments informed by concepts plus systems-level testbeds
With successively higher fidelity

Component Technology Focus: Electric Machines & Power Electronics

NASA Sponsored Motor Research

- 1MW
- Specific Power > 8HP/lb (13.2kW/kg)
- Efficiency > 96%
- Awards
  - University of Illinois
  - Ohio State University
- Phase 3 to be completed in 2018



Year 1 Technology Demo. Prototype Motor Parts

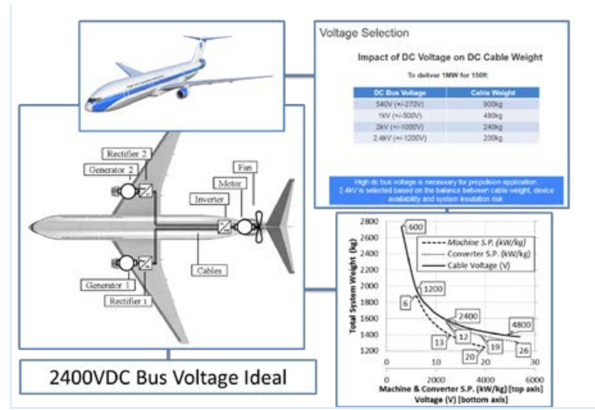
NASA In-House Motor Research

- Analytical Studies and Prototype Testing focused on ultra-high efficiency 99%

Fully Superconducting Electrical Machines

- Lower Fan Pressure + Boundary Layer Ingestion
- Superconducting (including transmission)
- ~4 MW Fan Motors at 4500 RPM
- ~30 MW Generators at 6500 RPM
- ~5-10 kV DC Bus Voltages
- End-to-end efficiency of Powertrain = 98%

System-driven Powertrain Trades



NASA Sponsored Inverter Research

- 1MW, 3 Phase AC output
- 1000V or greater input DC BUS
- Ambient Temperature Awards
  - 3 Years (Phase 1, 2, 3)
  - GE – Silicon Carbide
  - Univ. of Illinois – Gallium Nitride
- Cryogenic Temperature Award
  - 4 years (Phase 1, 2, 3)
  - Boeing – Silicon CoolMOS, SiGe

Ambient Inverter Requirements

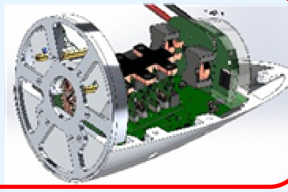
Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	12	7.3	98.0
Goal	19	11.6	99.0
Stretch Target	25	15.2	99.5

Cryogenic Inverter Requirements

Key Performance Metrics	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	17	10.4	99.1
Goal	26	15.8	99.3
Stretch Target	35	21.3	99.4

NASA In-House Inverter Research

- Designing 14 kW Inverter based on HEIST motor and nacelle cooling and packaging requirements
  - 99% efficiency driven by cooling requirements



Ongoing Contracts resulting from HGEP NASA Research Announcements

Concepts:

- “Hybrid Electric Geared Turbofan Propulsion System Conceptual Design,” United Technologies Research Center
- “Hybrid Gas-Electric Propulsion System,” Rolls-Royce LibertyWorks
- TBD awards from recent announcement: “Single Aisle Electrified Aircraft Design Concept”

Electric Machines:

- “High Speed, High Frequency Air-Core Machine and Drive,” University of Illinois
- “10 MW Ring Motor,” Ohio State University

Power Electronics: Inverters and Rectifiers:

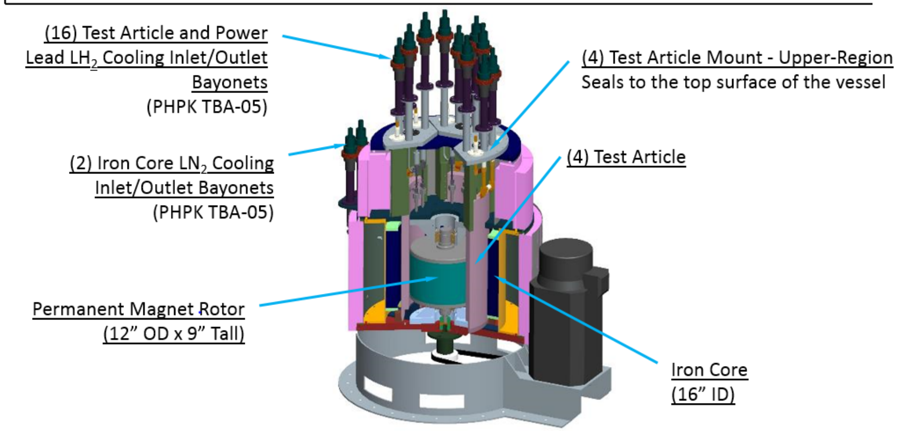
- “Silicon-Carbide Lightweight Inverter for Megawatt-Power,” GE Global Research
- “Ultra-light Highly Efficient MW-Class Cryogenically-Cooled Inverter for Future All-Electric Aircraft Applications,” Boeing Inc.
- “Modular and Scalable High Efficiency Power Inverter for Extreme Power Density Applications,” University of Illinois

Component Technology Focus: Electric Machines & Power Electronics

Fully Superconducting Electrical Machines

- SOA Superconductors unable to deliver req'd high current density, compactness, and low losses when exposed to stator's high alternating currents, fields (AC) and frequencies
- HGEP focusing on manufacturability of stator coils and coil test beds

Core Test Rig Concept



SC Coil Testbed (Core)

System-driven Powertrain Trades

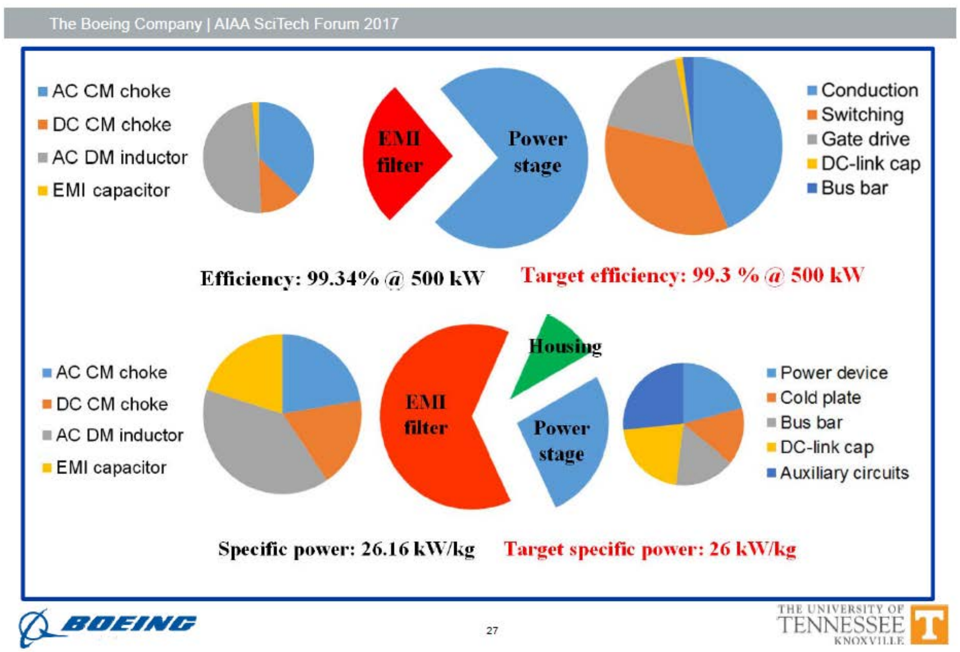
- HGEP focusing on manufacturability of stator coils and coil test beds
- Coil-testing at 20K in motor rig to establish good current carrying capability in stator coils
- LN2 coil-testing and motor rigs as a cost-effective way to establish measurement processes and to systematically study the AC loss issue
- Establish design, control, and methodology testing for fully superconducting designs, which utilize both AC & DC fields

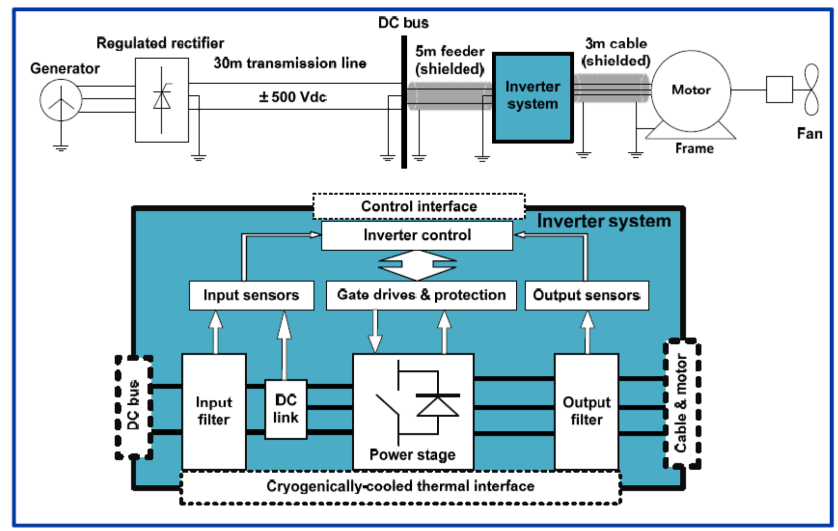
Component Technology: Status

Boeing Ultra-light Highly Efficient MW-Class Cryogenically-Cooled Inverter

- Power Semiconductors
- Topology
- Control and PWM
- Gate Drive
- NPC topology
- EMI Filter
- Cryogenic Cooling System

Cryogenic Cooling System





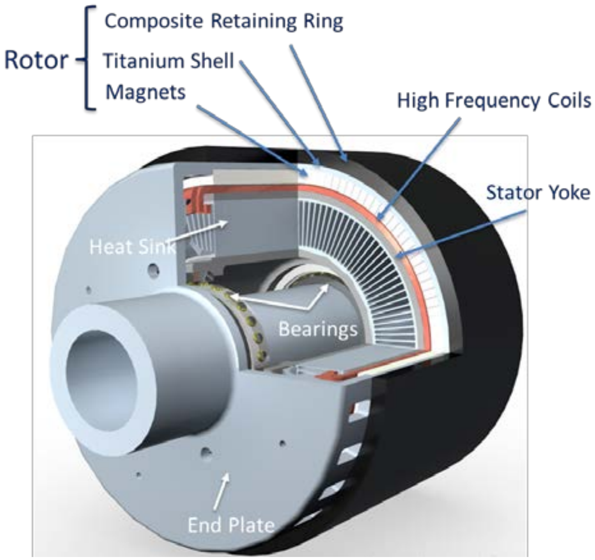
System Architecture

Shengyi Liu,, *Ultra-light Highly Efficient MW-Class Cryogenically-Cooled Inverter*, AIAA SciTech, January 9, 2017

Component Technology: Status

University of Illinois Motor and Inverter

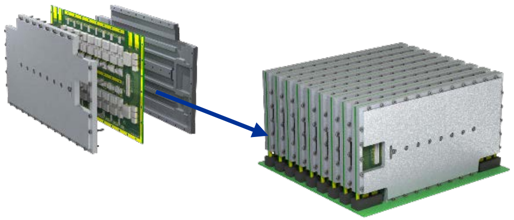
- Technology is promising – 13kW/kg at >96% efficiency achievable
- Design validated with computer modeling and component tests
- Key risk mitigation steps in 2017
- Opportunities/Challenges remain in system integration



"Air Core" Machine

key parameters	Values
rated power	1MW (Spec = 1MW)
rated efficiency	97.4% (Spec = 96%)
specific power	15kW/kg (spec = 13kW/kg)
total machine weight	144.2 lbs
machine active weight	75.7 lbs
sync. reactance	0.06 p.u.
insulation class	H
nominal speed	15,000 RPM
line to line voltage	650 V_{RMS}
DC bus voltage	±500 V
Cooling	Forced air, 20m/s

- Modular converter structure
  Redundancy, interleaving, scalability
- 13-level flying capacitor demonstrated
- High speed, high frequency motor drive



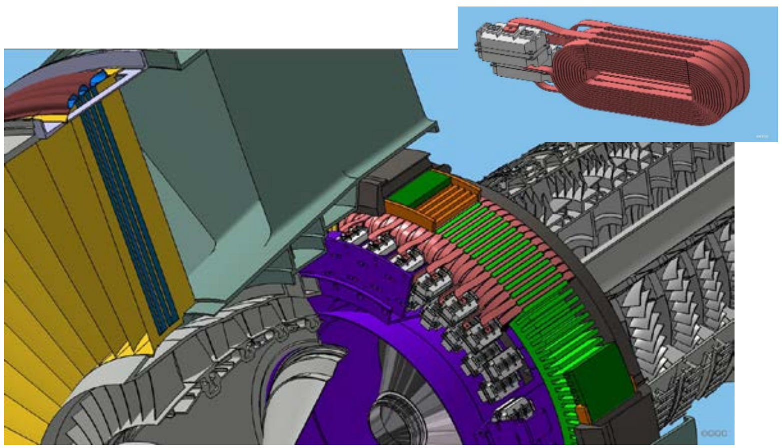
Flying capacitor, multi-level inverter

Kiruba S. Haran, *High Speed, High Frequency Air-core Machine and Drive*, AIAA SciTech, January 9, 2017

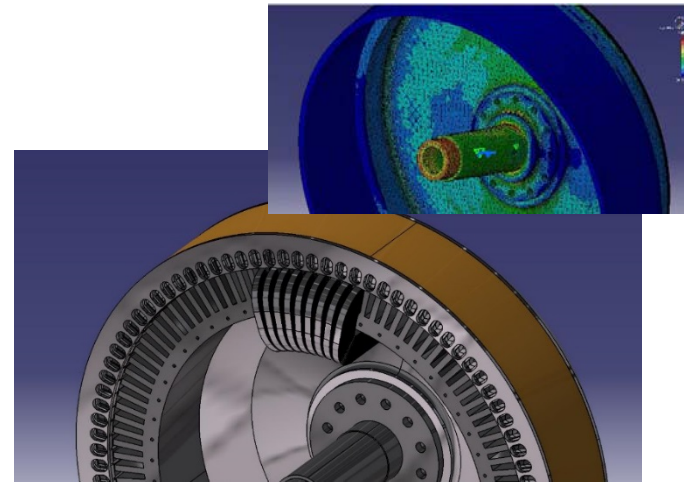
Component Technology: Status

Ohio State University 10 MW Ring Motor

- Completed 300kW Wet coil technology demonstrator motor
- Completed 1MW Motor Preliminary Design
- 500 kW demonstrator buildup underway (pushing for 1 MW)
- Investigated primary motor/turbine
- 4000 kVA inverter design (COTS-based)



Variable Cross Section Wet Coils (VCSWC) Demonstrator



- Ring VCSWC or Variable Cross-Section Wet Coils Distributed Power Electronic
- External rotor

After design optimization, showing possible 11.2 hp/lb, but some issues need to be resolved

Codrin-Gruie (CG) CANTEMIR , *10 MW Ring Motor*, October 2016 NRA Review
Codrin-Gruie (CG) CANTEMIR , *10 MW Ring Motor*, EnergyTech16

Component Technology: Status

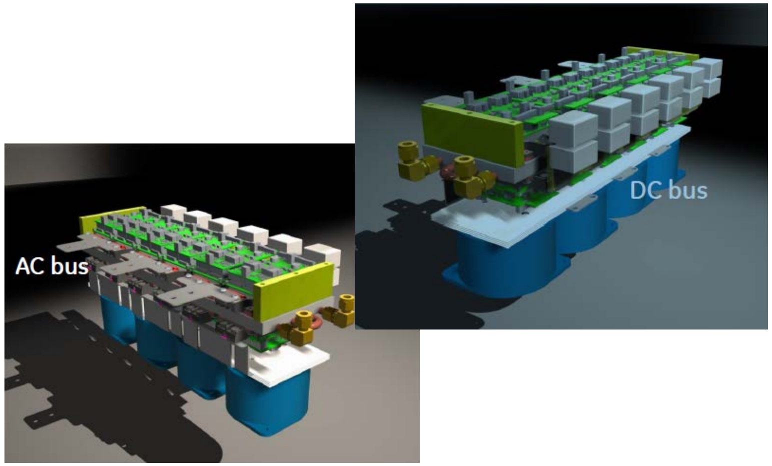
GE SiC Light-weight Inverter for MW-Power (SLIM)

Objectives:

- *Develop & demonstrate advanced inverter*
- *Design power conversion concepts*
- *Demonstrate scalable inverter system*
- *Implement silicon carbide power technologies*
- *Execute TRL 4 demonstrator of 1MW, 2.4kV inverter*

99.4% power stage efficiency can be achieved

- GE 1.7kV 500A SiC Dual module is used as the basic building block for SLIM.
- Classic Three level ANPC is selected as the topology of SLIM.
- Efficiency performance is verified by double pulse test results.
- Mechanical conceptual design is developed to meet the specific power density target.
- 1st 1MW demo unit will be built and tested in 2017.



Mechanical Layout - Concept

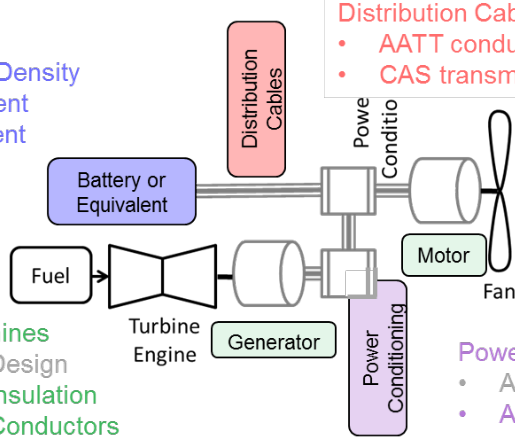
Di Zhang, NASA *SiC Light-weight Inverter for MW-Power (SLIM) – Phase I,* AIAA SciTech, January 9, 2017

Enabling Materials for Electrified Propulsion

Power System Weight Drivers

Improved Power Density
- OGA investment
- CAS investment

Distribution Cables
- AATT conductors
- CAS transmission cables



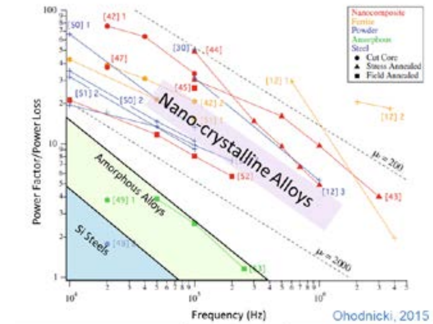
Elec. Machines
- AATT Design
- AATT Insulation
- AATT Conductors
- CAS Manufacturing

Power Condition
- AATT Design
- AATT Filtering

Magnetic Materials

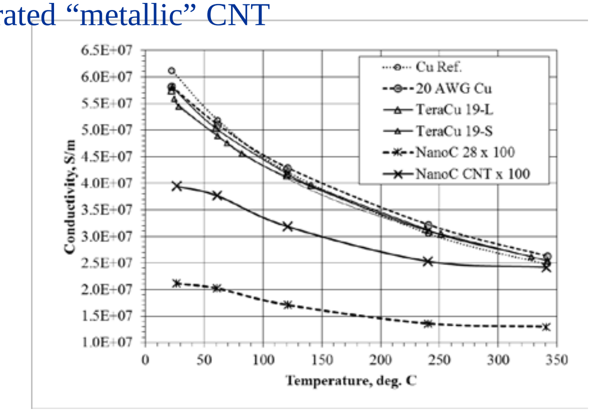
High Efficiency Component Development

- Inductor Filters – for 20 kHz ripple suppression in motor controllers
- DOE sponsored PV-to-grid integration transformer



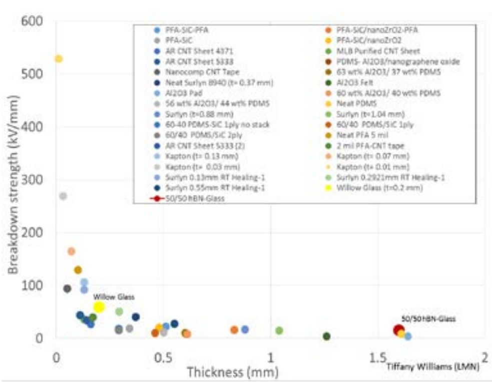
High Conductivity Materials

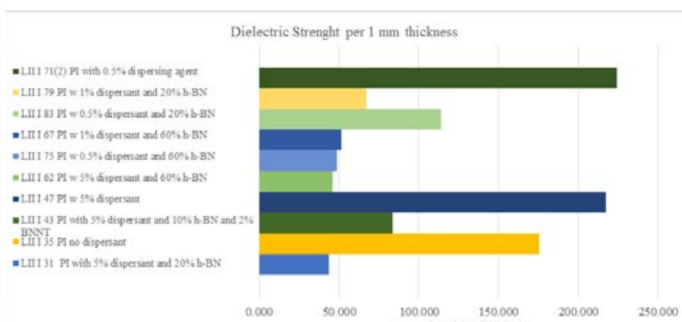
- Theoretically CNT or graphene has high conductivity
- Limited evidence of specific conductivity improvements
- Looking at separated "metallic" CNT



Insulation Materials

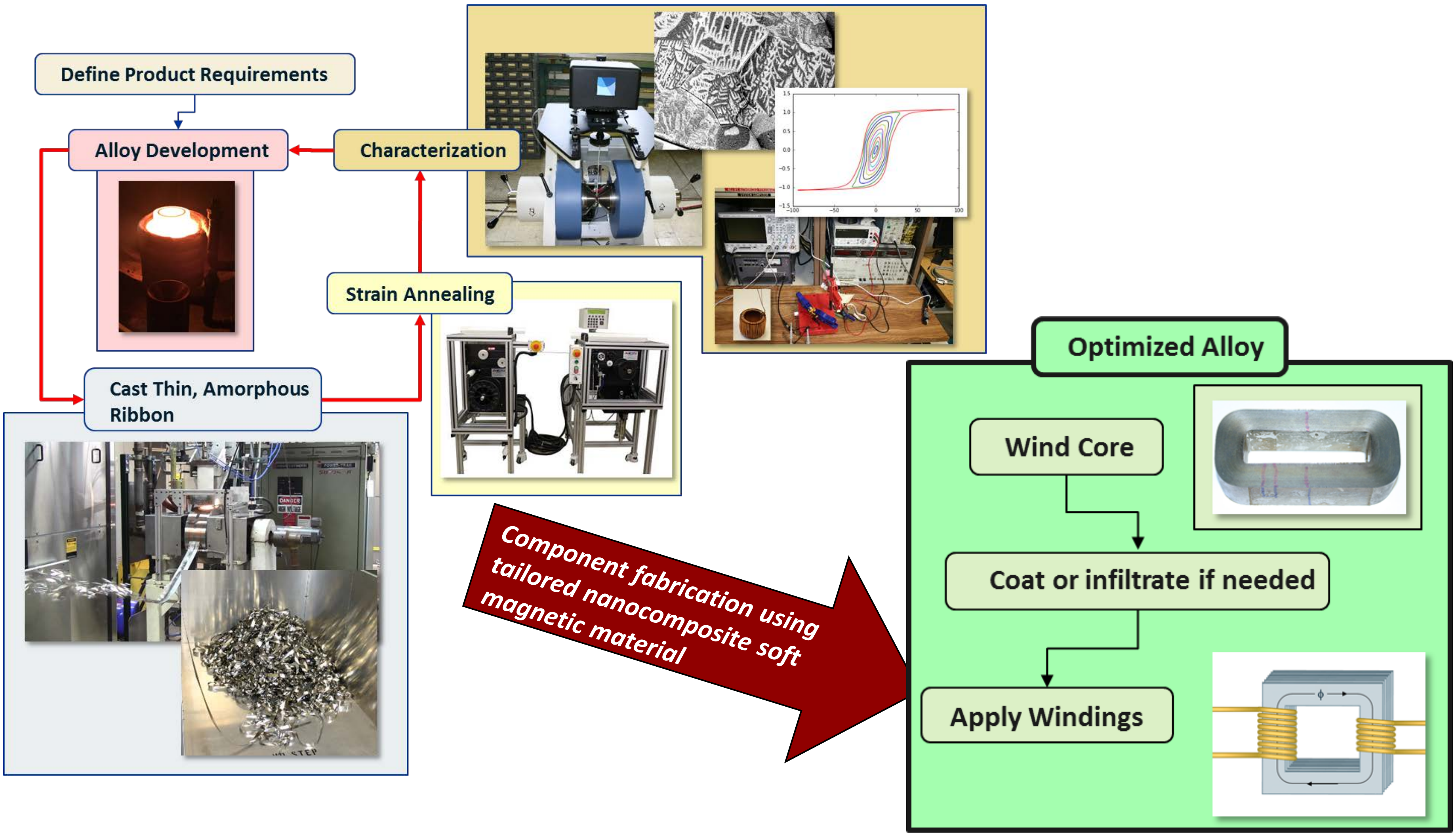
- Survey organic/inorganic composite solutions
- Quantify thermal bottlenecks
- Enable novel materials/engineering solutions



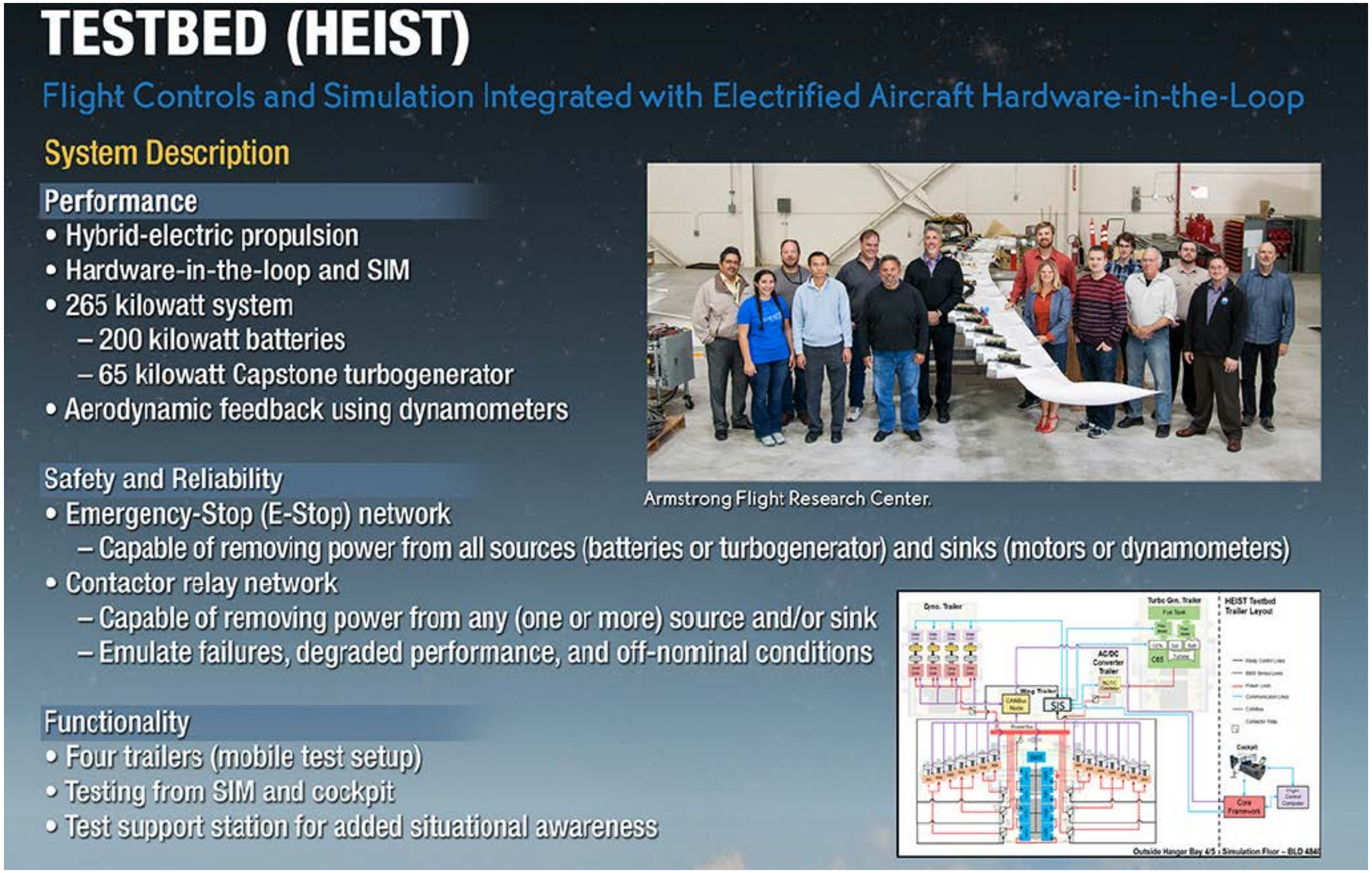


Enabling Materials for Electrified Propulsion

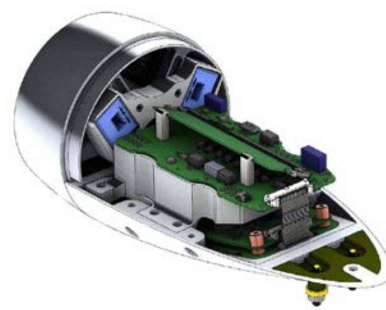
Complete cycle of alloy to component development for nanocrystalline soft magnetic materials



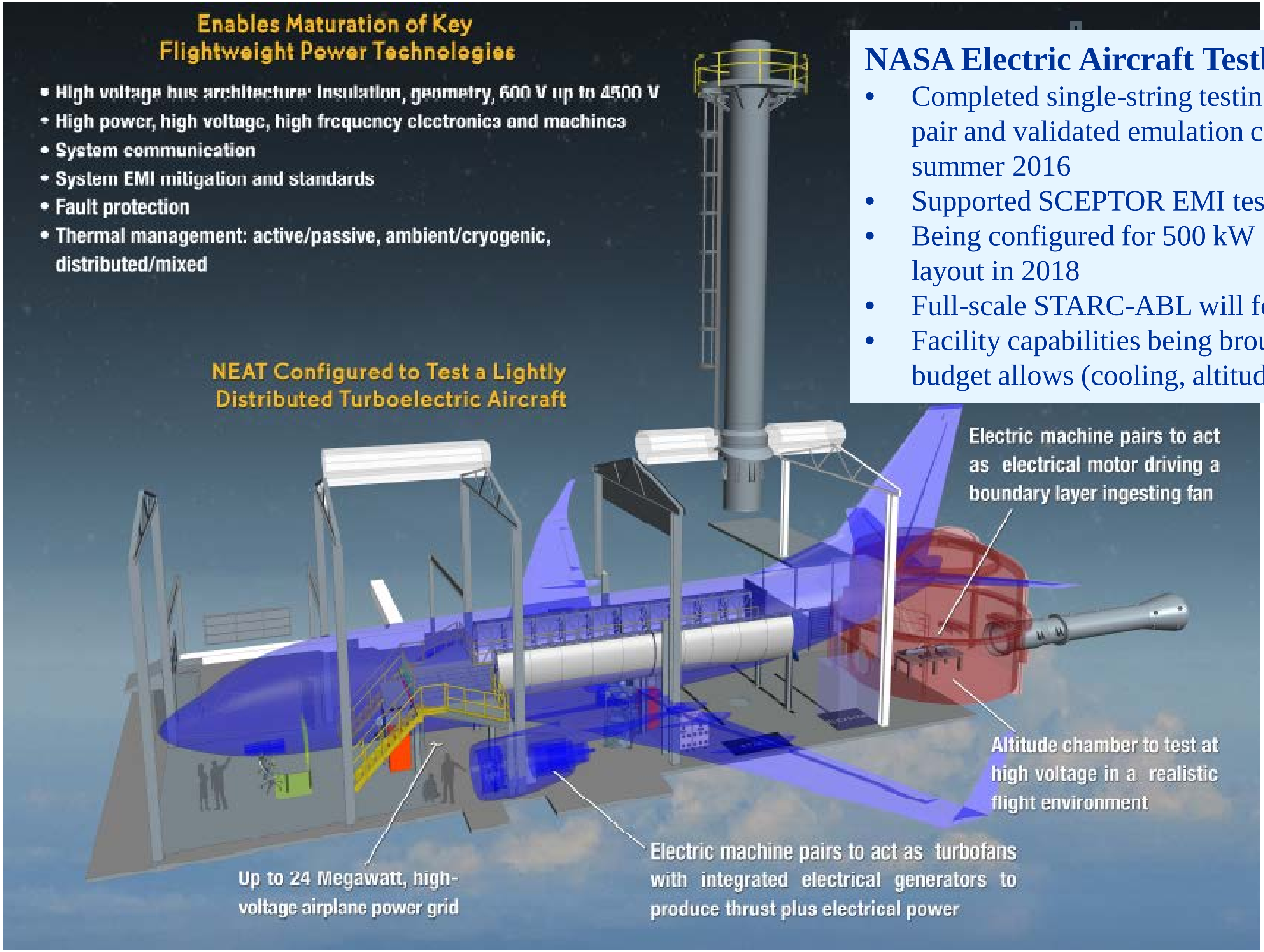
Testbeds - Status



- Completed Design Review for 1st Phase (100V battery-powered)
- Control dev’t underway
- Currently testing the heat sink motor for a passively cooled motor controller (in-house design, GIMC/HEIST)



Testbeds - Status



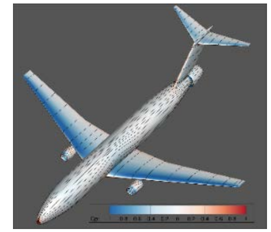
NASA Electric Aircraft Testbed (NEAT)

- Completed single-string testing of a motor pair and validated emulation concept in summer 2016
- Supported SCEPTOR EMI testing
- Being configured for 500 kW STARC-ABL layout in 2018
- Full-scale STARC-ABL will follow
- Facility capabilities being brought online as budget allows (cooling, altitude, cryo, etc)

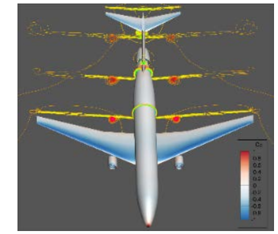
Concepts: Status

STARC-ABL

- Ongoing efforts for more in-depth analyses for vehicle concept
- High fidelity CFD being used to improve aerodynamics

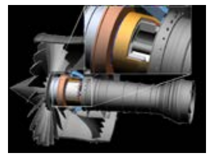


Surface coefficient of pressure and oil flow surface streamline visualization

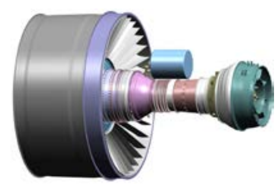


Surface coefficient of pressure and slices

Battery Parallel Hybrid



- Rolls Royce, “NASA Hybrid Gas-Electric Propulsion System”
- UTRC, “Parallel hybrid Geared Turbofan™ (GTF™) engine propulsion system”



ESAero ECO-150 Distributed Concept

- Phase II SBIR: *Continued Development of Environmentally Conscious "ECO" Transport Aircraft Concepts as Hybrid Electric Distributed Propulsion Research Platforms*

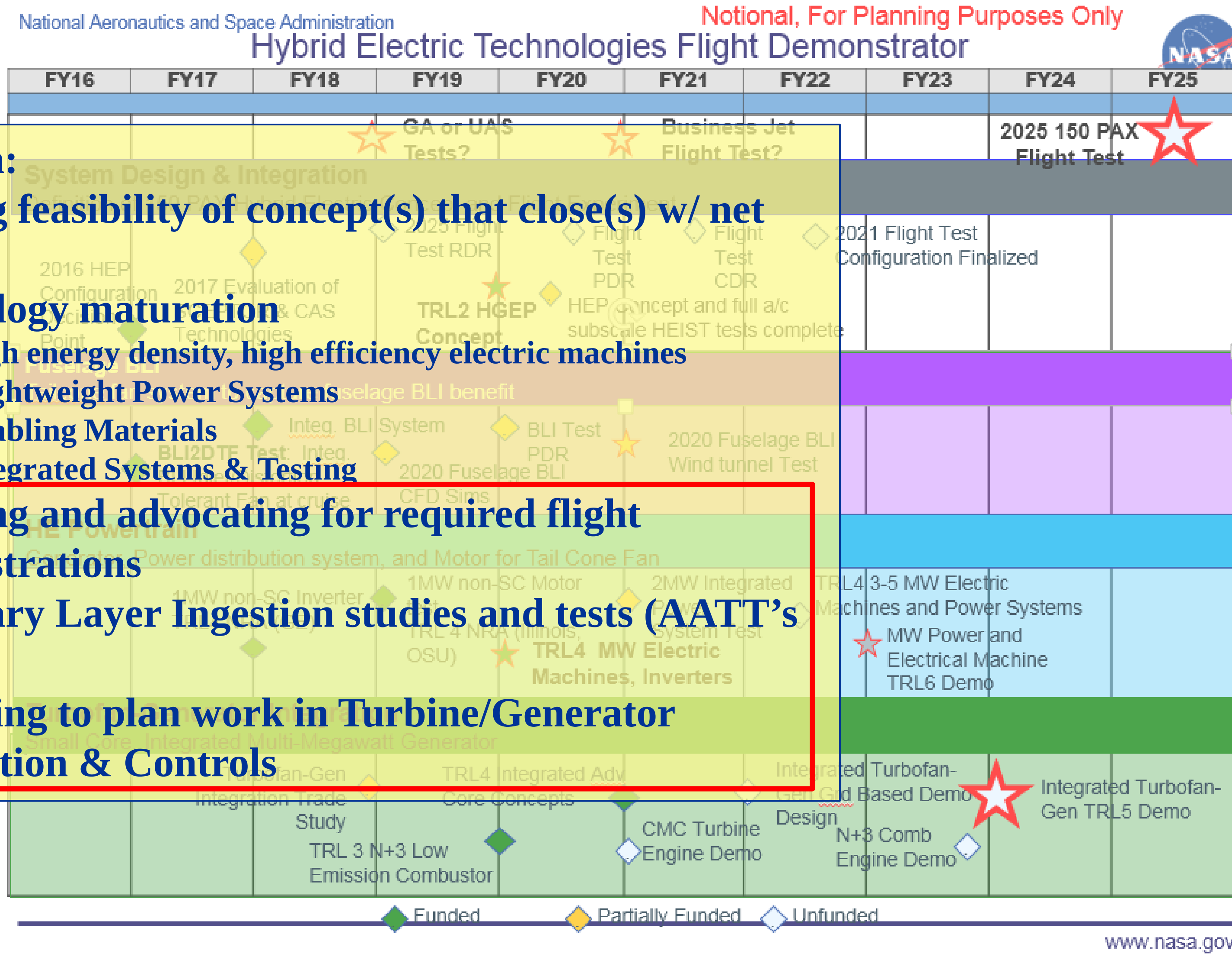
New Contracts resulting from NASA Research Announcement

- 12 month studies, objective vehicles for 2013 EIS
- Intended to help inform component technology investments, future flight demonstrator plans, gain industry perspective

Continuing Concept Refinement and Identifying Common Technology Requirements and Drivers

Michael Armstrong et al, *NASA Hybrid Gas-Electric Propulsion System Phase II Review*, October 2016
Chuck Lentz et al, *Phase II Review NASA Hybrid Electric Geared Turbofan Propulsion System Conceptual Design*, October 2016

HGEP Project



Focused on:

- **Proving feasibility of concept(s) that close(s) w/ net benefit**
- **Technology maturation**
  - **High energy density, high efficiency electric machines**
  - **Flightweight Power Systems**
  - **Enabling Materials**
  - **Integrated Systems & Testing**
- **Enabling and advocating for required flight demonstrations**
- **Boundary Layer Ingestion studies and tests (AATT's IBLI)**
- **Beginning to plan work in Turbine/Generator Integration & Controls**